Open Pit Mine Flooding Prognosis making use of Analytical Element Modelling in Fractured Hard Rock

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Abstract

A large number of South Africa's open pit mines are located in fractured rock. Analytical solutions to pit flooding mainly make use of the Dupuit-Forchheimer approximation. A typical example of such a solution is the solution proposed by Marinelli and Niccoli (2000). The challenge with most of these solutions is that the pit geometry is generally chosen as symmetrical and that the solution cannot accommodate geological structures. Numerical solutions to partial differential equations are available in the form of finite-difference, finite-volume and finite-element schemes. These solutions are able to solve for complex geometries and can accommodate geological structures, but require appropriate grid refinement to represent geological structures.

The analytical element method (AEM) is a numerical method used to solve partial differential equations. It was initially developed by Strack (1989). The method does not rely upon discretization of volumes or areas in the modelled system; only internal and external boundaries are discretized. The AEM allows the open pit to be modelled as an asymmetrical element with thin and irregular inhomogeneities, which can be used to represent geological features.

The AEM solution to pit flooding is more realistic than the typical analytical solution due to the relaxation of the pure analytical solution restrictions. This is especially true for scenarios where strip mining is simulated with continuous backfill taking place.

Applying the AEM solution to open pit flooding scenarios is a quick and effective way to obtain first order flooding results. The advantage is that elements e.g. inhomogeneities that constitute the model, can be switched on or off since they are not dependent on a specific grid. This allows for quick changes to the model, by introducing new elements or removing elements to determine their influence on the result obtained.

Key words: Open pit mines, geological lineaments, hard rock, analytical element method

Introduction

Mining in South Africa started in the mid 1800s and has been a key driver of the economy. There are two main mining approaches namely extraction by means of open pits or extraction by means underground workings. The approach chosen to mine a deposit is based on the maximization of profits given the unique characteristics of the deposit and its location, limits imposed by safety and environmental impacts. Both approaches present their own set of challenges but the focus of this paper will be on open pits.

An open pit mine can broadly be defined as a mine in which the deposit can be extracted by removing the covering layers of rock and soil and requires no roof support. Although the basic concept of an open pit is quite simple, the planning required to mine a large deposit is a very complex and costly undertaking. One of the key challenges is the management of water seeping into/flooding the open pit mine. The quantification of these volumes are dependent on a number of factors including:
- Size and the shape of the deposit
- Geology in which the deposit is located
- Conduits (e.g. fractures and faults) intercepting the open pit mine
- Barriers (e.g. dykes) intercepting the open pit mine

- Mining plan and method (e.g. strip mining)
- Mine closure options (e.g. backfilling and pit lakes)

While detailed three dimensional numerical modelling may be required in some studies, simpler methods for estimating open pit inflows can be informative and not so time consuming. The aim of this paper is therefore to motivate the use of the Analytical Element Method (AEM) as a tool calculate seepage/flooding volumes without having to to develop detailed finite-difference, finite-volume and finite-element numerical models which take time to setup, calibrate and can be computationally expensive.

Modelling Methods

The first method was developed by Marinelli and Nicoli (2000) and is based on the Dupuit-Forchheimer approximation. The flow into the pit is divided into 2 zones as shown in Figure 1. Zone 1 represents flow through the pit walls. Zone 2 represents the inflows from the base of the pit.
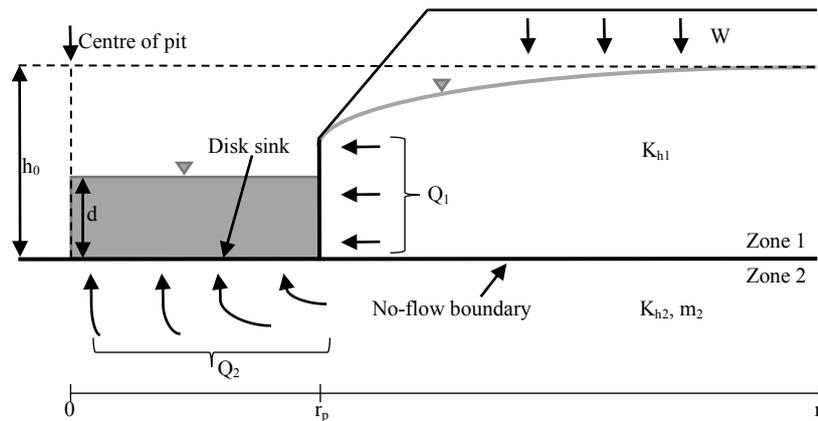

Figure 1 *Pit inflow model adapted from Marinelli and Nicoli (2000).*

The analytical equation for the inflow into the pit from Zone 1 can be expressed as:

$$Q_1 = W\pi(r_o^2 \text{-} r_p^2)$$

where

Q_1 = volumetric flow rate from Zone 1
W = recharge flux
r_o = radius of influence
r_p = effective pit radius

The analytical equation for the inflow into the pit from Zone 1 can be expressed as:

$$Q_2 = 4r_p\left(\frac{K_{h2}}{m_2}\right)(h_0\text{-}d) \ \text{ with } m_2 = \sqrt{\frac{K_{h2}}{K_{v2}}}$$

where

Q_2 = volumetric flow rate from Zone 2
K_{h2} = horizontal hydraulic conductivity
K_{v2} = vertical hydraulic conductivity
m_2 = anisotropy parameter
h_0 = pre-mining saturated thickness above base of Zone 1
d = depth of lake

The assumptions on which the analytical solutions for Zone 1 and Zone 2 are based are summarised in Table 1.

***Table 1*** *Assumptions (Marinelli and Nicoli 2000).*

Zone 1 Analytical solution	Zone 2 Analytical solution
Pit walls are approximated as circular a cylinder	The hydraulic head is initially uniform
Groundwater flow is horizontal	The disk sink has a constant hydraulic head equivalent to the elevation the water level in the pit
The pre-mining water level is horizontal	
Uniformly distributed recharge occurs	Flow to the disk sink is three-dimensional and axially symmetrical
Groundwater flow towards the pit is axially symmetrical	Materials are anisotropic and the principal directions are horizontal and vertical for hydraulic conductivity

The AEM is a numerical method used for the solution of partial differential equations. It does not rely on discretization of volumes or areas in the modelled system. Only internal and external boundaries are discretized. The basis of the AEM is that, elementary solutions may be superimposed to obtain more complex solutions. A number analytic solutions known as elements are available. These elements typically correspond to a dependent variable or its gradient along a boundary.

Each analytic solution is infinite in space and/or time. In addition, each analytic solution can be calculated to meet specified boundary conditions. To obtain a solution, a system of equations is solved such that the boundary conditions are satisfied along all of the elements. The governing equation is satisfied exactly except along the border of the element, where there is a discontinuity.

The ability to superpose numerous elements in a single solution means that analytical solutions allows for complex boundary conditions. Therefore, models that have complex geometries, multiple boundaries, transient boundary conditions etc. can be solved.

The AEM has been applied in modeling open pit mines and shows reasonable results compared to that of finite-element and finite-difference models for the same study area. Monthly simulated pit inflow values making use of AEM for the groundwater component and accounting for direct rainfall into pit and evaporation is shown in Figure 2.
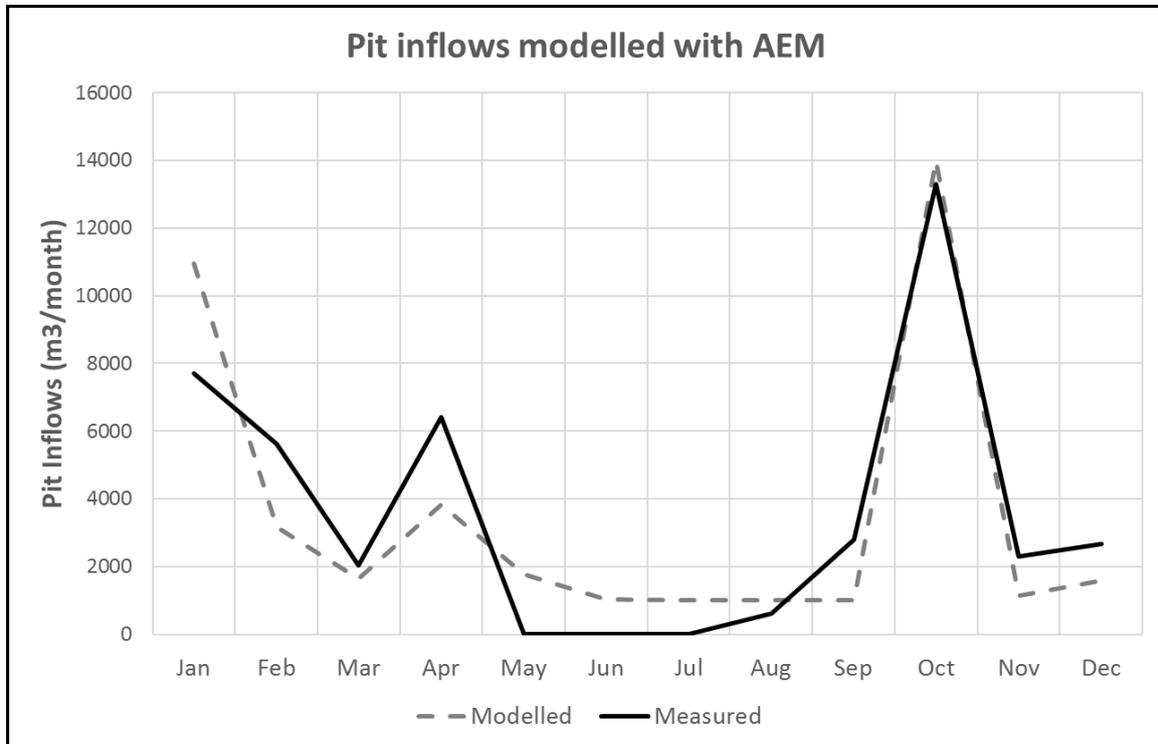
Figure 2 *Example of modelling results.*

Limitations include that the Dupuit-Forchheimer conditions are valid which include Craig (2007):

- Hydraulic heads may be represented by its average value in the vertical direction

- Resistance to flow is negligible in the vertical direction

- The vertical flux is calculated by means of a mass balance and not Darcy's Law.

The AEM has limitations, but provides a flexible modelling tool when considering it is not dependent on a predefined grid with the ability to switch hydrogeological features in and off in a simulation with the click of a button. The method is capable of handling a range of applications, from simple screening models, to regional models multilayer models (Hunt, 2006).

Study Area

The layout of the study area is shown in Figure 3 and comprises two open pits, Pit A and Pit B. To the south of the study area is a river and to the north is a geological fault considered to be a high transmissive zone which intersects Pit A. The geology is characterized by predominantly norite and for the purpose of this paper only a single layer model is considered for comparison purposes. The light grey contour lines in Figure 3 represent the surface topography.

There are eight boreholes located within the study area. The comparison of average water level with surface elevation is presented in Figure 4 which shows a strong correlation between surface topography and water levels. Note that BH2 is close to Pit A and has a relatively deeper water level compared with other observation boreholes and therefore was not used in the linear regression calculation.

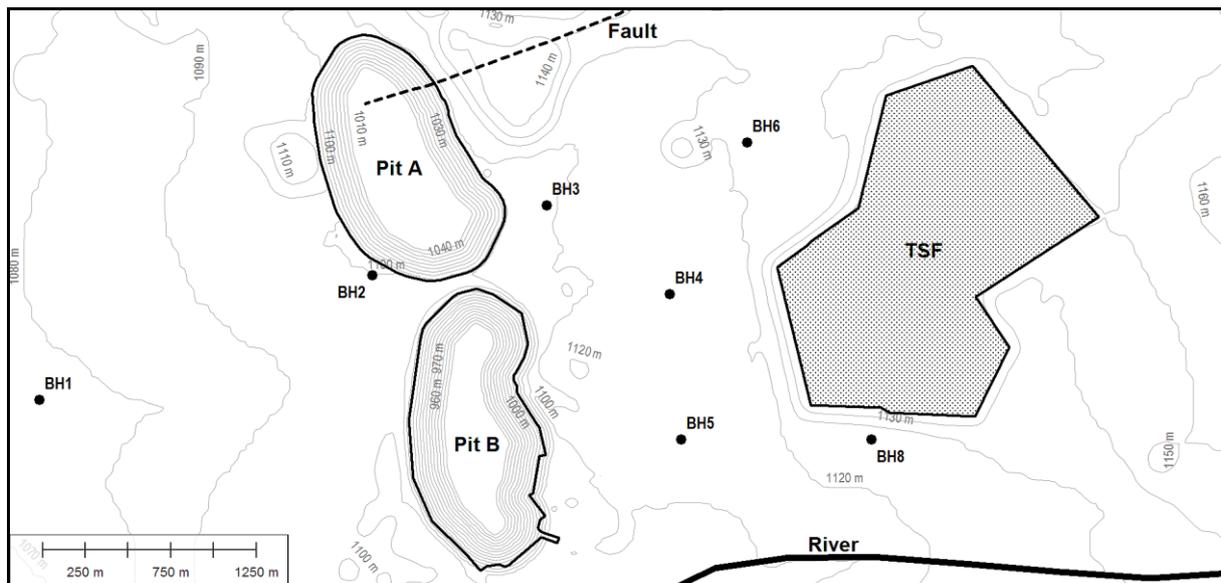A summary of the study area parameters used for modelling is listed in Table 2.
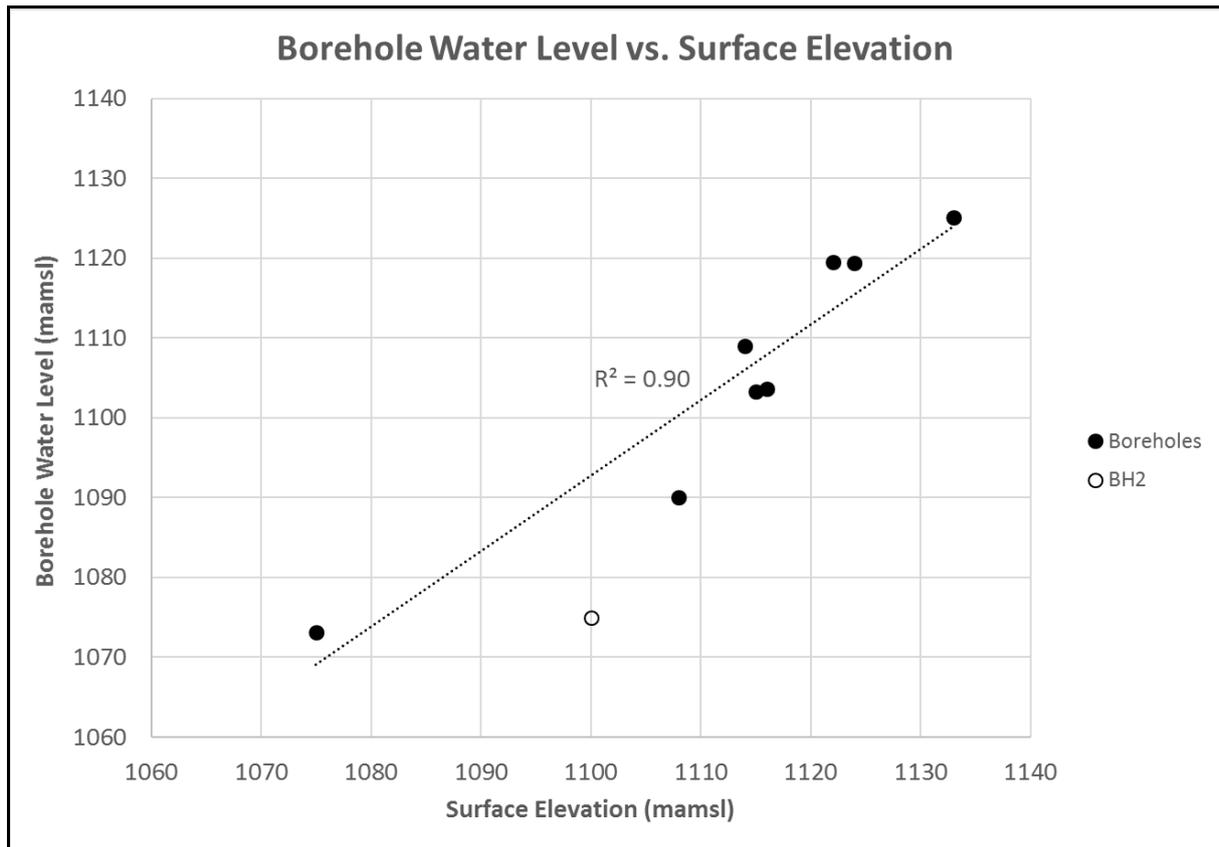

Figure 3 Layout of study area.

Figure 4 Correlation between groundwater levels and elevation.

Table 2 Parameters.

Parameter	Value
Mean Annual Precipitation (mm/a)	52
Recharge as % of MAP	3.0
Average Water Level (mbgl)	6.8
Norite Hydraulic Conductivity (m/d)	0.02
Fault Hydraulic Conductivity (m/d)	2.0
Aquifer Thickness (m)	200
Geological Fault Width (m)	2
Pit A - Surface Elevation (mamsl)	1100
Pit A – Depth (m)	100
Pit B – Surface Elevation (mamsl)	1070
Pit B – Depth (m)	110

Modelling Methodology

Both pits in the study area are modelled with the analytical solution proposed by Marinelli and Niccoli (2000). The same system is then modelled by making use of the AEM which can account for both the pit interference and the high transmissive geological fault feature.

Using Marinelli and Niccoli (2000), the first step is to transform the pit geometry to an equivalent cylinder represented by a pit radius. The pit floor geometry is used as the representative pit geometry for the purpose of this paper. The geometrical pit transformation can be done either by using the physical pit area or the physical pit perimeter. Two very different radii can be the result, as illustrated in Figure 5. This figure shows some typical examples together with the 1:1 line which will represent a perfect circle.
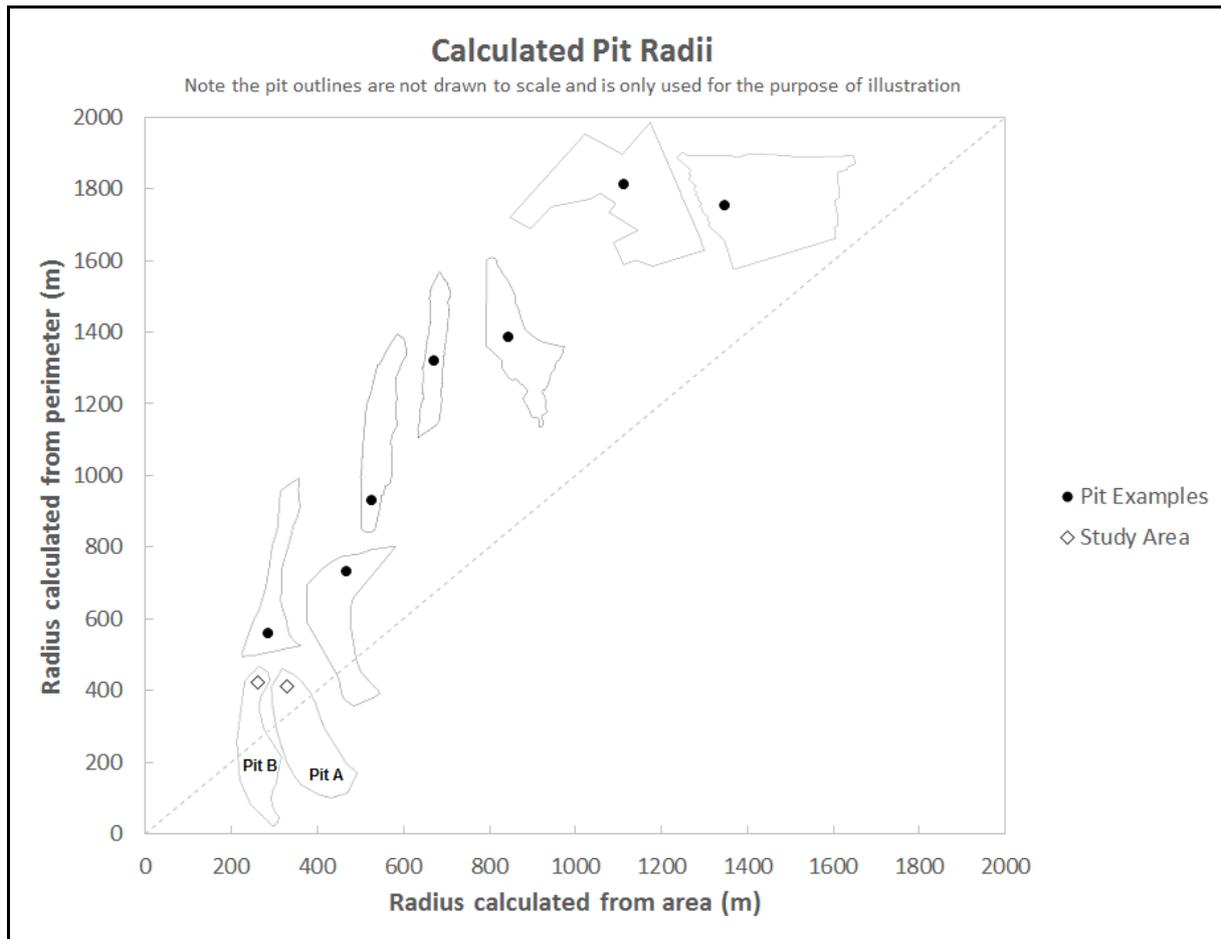
Figure 5 Calculated pit radii.

The calculated radii for Pit A and Pit B are presented in Table 3. The AEM results showed a better correlation with the pit radii calculated from the physical pit perimeter and was therefore used in the modelling. It is clear from Table B that the radii calculated through the pit perimeter represents a larger area than the physical pit area, therefore it is important to use the physical pit area if water balance calculations are performed and not the area represented by the newly calculated pit radius.

Table 3 Pit radii.

Pit Name	Area (m²)	Perimeter (m)	Radius from Area (m)	Radius from Perimeter (m)
A	339627	2583	329	411
B	216644	2655	263	423

Only a single layer model is considered for the study area and therefore the horizontal hydraulic conductivity for both Zone 1 and Zone 2 (see Figure 1) are set to 0.02 m/d. The vertical hydraulic conductivity for Zone 2 is used to calibrate the analytical model results of Pit A to that of the analytical element model of Pit A for comparison purposes. Pit A is selected for the calibration procedure as its geometry is closer to that of a circle than that of Pit B (see Figure 3).

Due to the fact that the analytical solution does not make provision for modelling a fault, which is a high transmissive zone in this case, an effective hydraulic conductivity is calculated for Pit A. The effective hydraulic conductivity (K_{eff}) for the cylindrical pit is calculated by assuming a skin around the cylinder consisting of the matrix hydraulic conductivity (K_m) and the geological fault hydraulic conductivity (K_f) as shown in Figure 6. Equation 1 is used to calculate K_{eff}, where L is the length of the associated hydraulic conductivity along the circumference of the pit.
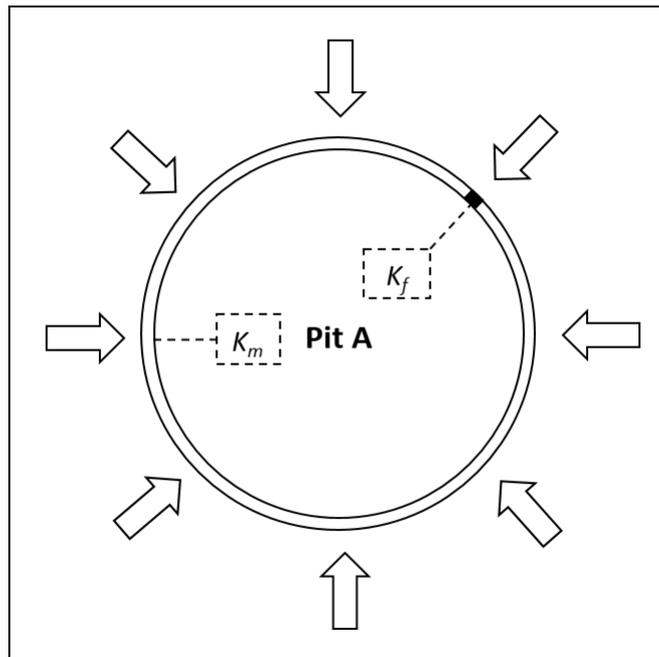
Figure 6 *Various hydraulic conductivity values.*

$$K_{eff} = \frac{(L_m K_m) + (L_f K_f)}{L_m + L_f}$$ (1)

A Visual AEM model is setup. In addition to the standard aquifer parameters the digital elevation model and a river are introduced in the model and calibrated making use of the observed water levels. Note the parameters presented in Table 2 are already the calibrated parameters.

Model Results

The comparison of the two models and their results are presented in Table 4.

Table 4 *Model results.*

Scenario Description	AEM Pit Inflow (m³/d)		Analytical Solution (AS) Pit Inflow (m³/d)		AS/AEM (%)	
	Pit A	Pit B	Pit A	Pit B	Pit A	Pit B
Single pits considered in isolation from each other	1675	1914	1675	1857	100%	97%
Only Pit A with geological fault	1746	*	1720	N/A	103%	*
Pit A and Pit B simultaneously, without the geological fault	1142	1369	*	*	*	*
Pit A and Pit B simultaneously, with the geological fault	1211	1364	*	*	*	*

* Scenario not applicable

Conclusions

It is well known that the open pit analytical solution proposed by Marinelli and Niccoli (2000) provide a convenient means for estimating groundwater inflows to open pits. The primary value of such analytical solutions is providing preliminary estimates to be used in the initial phases of mine planning. It has further been shown that for a single pit, an effective hydraulic conductivity can be calculated to account for a high transmissive geological fault and applied to the analytical solution proposed by Marinelli and Niccoli (2000).

A good correlation exits between the AEM and the open pit analytical solution of Marinelli and Niccoli (2000) when only single pits are considered. This is even the case for a high transmissvive geological fault is included by means effective hydraulic conductivity.

When considering more than just a single pit, a model is required that adequately describes the system in question. The AEM model allows the modelling of multiple open pits together with inhomogeneities and other hydrogeological features. The model does require calibration, but is grid independent, allowing the addition of various hydrogeological features which can be switch on or off with the click of a button to interrogate various scenarios. The model further makes use of the physical pit geometry and no translation to an equivalent feature is required.

References

Craig J (2007) The Analytic Element Method. Presentation for EARTH 661: Analytical methods in Hydrogeology, University of Waterloo

Hunt RJ (2006) Ground Water Modeling Applications Using the Analytic Element Method. Ground Water, Vol 44, No 1, 5 - 15

Marinelli F, Niccoli WL (2000) Simple analytical equations for estimating groundwater inflow to a mine pit. Ground Water, Vol 2, No 3, 311 - 314

Strack ODL (1989) Groundwater Mechanics. Prentice Hall, Englewood Cliffs, NJ